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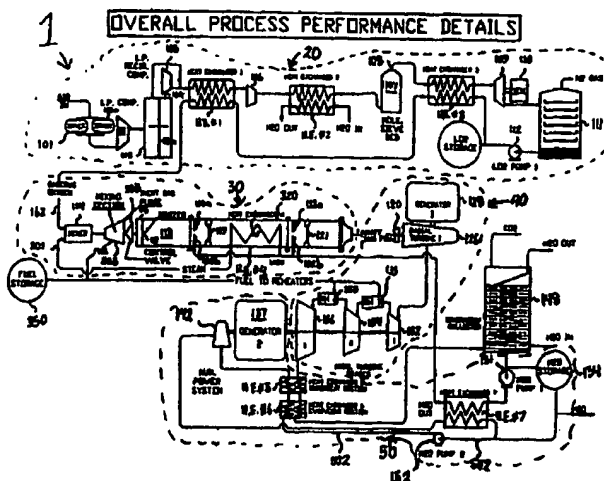
(57) **Abstract**

　A low pollution gas generator includes a source of a mixture of oxygen rich gas and fuel, the oxygen rich gas having less nitrogen than air and more oxygen than air. The mixture is passed into a combustion chamber where it is ignited. The premixing of the oxygen and fuel prior to entering the combustion chamber allows for more efficient combustion. Water is used as a heat absorbing agent. The mainstream gases from the combustion chamber expand through a primary turbine and then are reheated before expanding through a secondary turbine. Heat from the mainstream gases is transferred to an auxiliary flow of water which becomes steam and is expanded through an auxiliary turbine. The system of the present invention may obtain efficiencies of 65 % or even higher. Furthermore, this system provides little or no pollution and is compact compared to industrial power generation systems of similar power output.

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AN ADVANCED TECHNOLOGY
POLLUTION FREE, HIGHLY EFFICIENT
INDUSTRIAL POWER GENERATION SYSTEM

5

BACKGROUND OF THE INVENTION

10   Air pollution, commonly called "smog", is a very serious problem in most
major metropolitan cities. Smog includes sulfur dioxides and nitrous oxides which
form a brown cloud in the surrounding air. While much of the smog comes from
automobiles, trucks, and busses, other sources of smog include the power
generation industry, for example, which burns coal, natural gas and/or oil to
15   produce electrical power.
        Steam and gas turbines have been used to produce electricity for many
years. In the early days, coal, wood, kerosene or other petroleum products were
burned to produce the heat necessary to convert water to steam at reasonably high
pressures (e.g., from 500 to 1000 PSIA). The steam was then exhausted into a
20   turbine stage or series of turbine stages to turn the thermal energy of the steam into
mechanical energy as shaft horsepower from the turbine. The turbine shaft was
connected to an electrical generator where the shaft horsepower was converted into
electrical power produced as alternating current. This power was transmitted as
electrical energy for everyday use.
25   Early industrial power generation systems utilized crudely designed
inefficient turbines and operated at low pressure and temperature. Combustion of
the fuel depended on trial and error methods for stoking the flame. The hot air
produced by the flame was flowed over a series of pipes, through which flowed
water, to produce steam. Overall efficiencies for producing electricity were very
30   low (approximately 10% of the lower heating value of the fuel), and the pollution
of the surrounding environment was very high. In those days, the pollution was
caused by the smoke and haze generated by the combustion process, and the carbon
dust deposited out of the smoky exhaust.
        As industrial power generation systems improved, smog, acid rain, and the
35   greenhouse effect became of concern. More efficient turbines, better flame control
in the combustion chamber, and much improved heat transfer systems have helped

lift the overall efficiency of these systems to approximately 30-35%, with
minimum output of any dark smoke (unburned hydrocarbons). However, smog,
acid rain, and the greenhouse effect still plague the existing industrial power
generation systems that use fossil fuel and air.

5   Recent power generation technology developments have made use of a
combined cycle for producing electricity. An example of a combined cycle power
generation system is disclosed, for example, in an article authored by Victor de
Biasi appearing on pages 17-22 of the March-April 1984 edition of Gas Turbine
World, entitled *A Look into Real Payoffs for Combined Cycle Conversions*, which
10   article is incorporated herein by reference in its entirety. Combined cycle systems
use a gas turbine much like that used in an airplane to drive the primary power
generator. A series of axial flow compressor stages boosts the pressure of the
incoming air up to combustion pressure in the gas generator where it is mixed with
fuel and ignited. The hot gases are then exhausted into a series of turbine stages
15   where the heat energy is turned to work in terms of shaft horsepower. The shaft
horse power is then turned into electrical power in the generator. The relatively
warm gases exiting the last turbine stage are used to heat up a separate steam
source that powers a steam turbine for producing more electrical power, from
which comes about the term, "Combined Cycle". Advantageously, this system
20   boosts the overall efficiency of the system for producing power generation to
approximately 45-50%. However, this system still pollutes generating smog, acid
rain and greenhouse gases. To lower pollution, catalysts are used in the
combustion chamber, sulfur is removed from the incoming fuel, and water is
injecting into the combustion chamber to lower nitrous oxide formation. While
25   these techniques show promise, they will never be able to eliminate the pollution
entirely. Therefore, a low pollution industrial power generation system that is
more efficient than conventional systems is needed.

          In addition to the polluting, the conventional industrial power generation
systems are relatively large, often generating hundreds of megawatts or even
30   gigawatts of power and occupying many acres of land. An inadvertent shut down,
for example, of an industrial power generation system may impact the quality of
electricity supplied to consumers if the other generating systems in the electricity
network are not equipped to compensate for the shut down. Furthermore, these
industrial power generation systems are too large for a smaller consumer (such as a
35   train or ship) to have their own systems. Therefore, individual business, schools,
and residential communities are typically forced to rely on outside sources of

electricity. These outside sources have complex distribution systems in which
much power is lost in the transmission to the consumer. Furthermore, the
consumer may be forced to pay unreasonably high prices for electrical power from
an outside source.

5   Accordingly, there is a need for an industrial power generation system
which (1) produces little or no pollution, (2) is more efficient, (3) is more compact,
(4) has long life and lower maintainence and operating costs, (6) and has short start
up and shut down time.

10

SUMMARY OF THE INVENTION

           In accordance with the present invention, a low pollution industrial power
generation system has a source of fuel and source of oxygen rich gas having less
15   nitrogen (e.g., no nitrogen) than is present in air and more oxygen than is present in
air. A mixing unit is configured to receive and mix at least the oxygen rich gas and
the fuel to form a mixture. In some embodiments, the oxygen rich gas is mixed
with steam prior to being mixed with the fuel. A combustion chamber is in
selective fluid communication with the mixing unit through a valve. Within the
20   combustion chamber, an igniter is configured to ignite the mixture downstream of
the injector face. In one embodiment, the system is closed loop and emits no
pollution.
           In accordance with the present invention, a low pollution industrial power
generation method includes providing a source of fuel and source of oxygen rich
25   gas having less nitrogen than is present in air and more oxygen than is present in
air. A mixing unit receives and mixes at least the oxygen rich gas and the fuel to
form a mixture. Combustion chamber walls define a combustion chamber which
receives the mixed fuel and oxygen rich gas from the mixing unit. An igniter
within the combustion chamber ignites the mixture downstream of the injector
30   face.
           In the exemplary embodiment described herein, steam (a heat absorbing
medium) and oxygen rich gases (e.g., substantially pure oxygen) are premixed in
one chamber and then introduced to a second chamber where fuel (e.g., methane) is
added and mixed. The uniform mixture of gases is then injected through an
35   injector face into a combustion chamber where burning is initiated by an igniter,

typically but not necessarily, at the center of the injector face. Combustion chamber pressure is on the order of approximately 3300 PSIA.

When combusting a conventional air/fuel mixture, the essentially inert nitrogen (78% of the air by volume) of the air is a heat absorbing medium which absorbs a large portion of the combustion generated heat. This nitrogen thus lowers the combustion temperature compared to the combustion temperature if no heat absorbing medium was used. The industrial power generation system of the present invention reduces or eliminates the amount of nitrogen used as a heat absorbing agent. Instead, a heat absorbing agent other than nitrogen such as H_2O is used to reduce nitrous oxide emissions. As a feature of this invention, water is added to the combustion process. The water in the fuel/oxygen mixture is a more efficient heat absorbing medium than is nitrogen in the fuel/air mixture because water can absorb more heat per unit mass. Since water is a product of the combustion process, this water is simply recirculated from the end of the power cycle back to the combustion inlet in a manner described in more detail hereinafter. Therefore, the exemplary embodiment reduces or eliminates nitrous oxide emissions and provides an efficient way to absorb combustion heat. In addition, the mixing of the fuel and oxygen prior to entering the combustion chamber promotes efficient combustion thereby improving the combustion efficiency of the power generation system.

An industrial gas generator comprises a source of heat absorbing agent in a liquid phase (e.g., in one embodiment, a water reservoir although other liquids can also be used if appropriate). Combustion chamber walls define a combustion chamber and define channels which fluidly connect the reservoir with the combustion chamber and thus allow water to pass from the reservoir to the combustion chamber. The liquid phase heat absorbing agent (e.g., water) is injected through the channels. As the liquid phase heat absorbing agent passes through the channels, it absorbs heat from the combustion chamber through the combustion chamber walls. The heat absorbing agent evaporates before entering the combustion chamber, thereby cooling the combustion chamber walls.

An industrial gas generation method includes providing the heat absorbing agent in a liquid phase, and passing the heat absorbing agent through the combustion chamber walls to the combustion chamber thereby cooling the combustion chamber walls. Typically, the heat absorbing agent in a liquid phase passes through channels defined in a combustion chamber wall and into a combustion chamber, wherein the heat absorbing agent changes from a liquid

phase to a gaseous phase as the heat absorbing agent passes through the plurality of channels and thereby cools the combustion chamber walls.

This type of cooling is called transpiration cooling. Water is very effective for this purpose since use is made of the latent heat of water as well as its sensible heat. Latent heat is the heat required (usually measured in BTU/ pound of H_2O) to evaporate and/or condense water and/or steam at saturation conditions. For water, this amounts to 900-1000 BTU/pound of H_2O. It takes a temperature change of approximately 1900°F in sensible heat content of H_2O in order to provide an equivalent heat change. Therefore, the present invention permits the combustion temperature within a power generation system to be even higher than the melting point of the material of the combustion chamber walls because these walls are cooled to below the melting point temperature if an adequate flow of water is provided through the openings in these walls into the combustion chamber.

In accordance with the present invention, a low pollution industrial power generation system includes a gas generator. The gas generator includes a combustion chamber portion which is configured to generate mainstream gases. A primary turbine stage is downstream of the combustion chamber, a reheater is downstream of the primary turbine stage, a secondary turbine stage is downstream of the reheater, and a heat exchanger is downstream of the secondary turbine stage. The heat exchanger is configured to transfer heat from the mainstream gases to an auxiliary fluid flow. An auxiliary turbine stage is configured to receive the auxiliary fluid flow and generate additional electricity from the auxiliary fluid.

In one embodiment of the present invention, an industrial power generation method includes combusting oxygen rich gases in a combustion chamber to form mainstream gases, expanding the mainstream gases from the combustion chamber through a primary turbine stage, reheating the mainstream gases from the primary turbine stage, expanding the mainstream gases from the reheater through a secondary turbine stage, transferring heat from the mainstream gases from the secondary turbine stage to an auxiliary flow, and expanding the auxiliary flow in an auxiliary turbine stage. Each stage generates electricity thereby increasing the efficiency of the overall power generating system relative to the prior art.

Turbines transform heat into mechanical energy to drive an electrical generator. With each turbine stage the gas temperature drops as the heat content is incrementally reduced, thereby reducing the energy derived from each subsequent stage. Installing reheaters between stages permits an increase in gas energy content such that the subsequent stage or stages are capable of yielding more overall

electrical power. In the exemplary embodiment, the reheat is accomplished by adding a small amount of fuel to the oxygen rich mainstream gases. Since the gas ignition temperature is less than the actual gas temperature in the reheater, combustion takes place spontaneously without an external ignition source. Since

5   the pressure ratio across each series of turbine stages is essentially constant, the potential power delivered by each stage is essentially the same when the inlet temperatures are identical. In contrast, without reheat stages, the energy delivered by each stage continually decreases resulting in a lower overall cycle efficiency.

Auxiliary steam power generation converts, into electricity, most of the

10   heat remaining in the mainstream gases after most of the pressure has been used by the primary and secondary turbine stages. The mainstream gases are brought back to essentially ambient conditions through heat transfer to steam in a steam power generation system. The use of the heat and pressure of the mainstream gases increases the overall efficiency of the power generation system.

15   The power necessary to drive all the pumps is negligible compared to the total system output power. The invention allows systems to be build with a wide range of power outputs. A typical system in accordance with this invention could produce a total power output of, for example, 12.56 megawatts using a pump power of only about 195 kilowatts resulting in a net power output of, for example

20   12.36 megawatts. Initial computations of the cycle efficiency of the exemplary embodiment indicate a 68.7% efficiency when excluding the power required to separate the oxygen from air. The efficiency drops down to approximately 65% when the power needed to separate oxygen from air is included. These efficiencies are higher than those of existing systems, even though the exemplary embodiment

25   emits no pollutants. Higher turbine inlet temperatures using turbine cooling and high temperature ceramics for the turbine blades can improve this performance even further.

The principles of the present invention are described in more detail in the following description and the accompanying claims.

30

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows schematically the overall industrial power generation system

35   showing how each of the individual systems is related in accordance with the present invention.

Fig. 2 shows schematically the oxygen production system of Fig. 1.

Fig. 3 shows schematically the gas generator of Fig. 1 with subsequent gas treatment systems prior to the gas entering the gas turbines.

Fig. 4 shows schematically the radial and axial turbines used in the main
5   power system of Fig. 1 to produce the electrical power and shows the interstage reheat systems.

Fig. 5 shows schematically the auxiliary steam power system of Fig. 1 that recovers waste heat from the main power system.

Fig. 6A shows an exploded isometric view of two flat ring-shaped platelets
10   which are part of the series of platelets shown in Fig. 3 used to transpiration cool the combustion chamber.

Fig. 6B shows a detailed exploded isometric view of a portion of Fig. 6A showing channels within the platelets.

Fig. 7 shows an isometric view of an embodiment of a reheater used in
15   accordance with the principles of the present invention.

Fig. 8A shows an exploded view of a platelet heat exchanger used in accordance with the principles of the present invention.

Fig. 8B shows the platelet heat exchanger of Fig. 8A in an unexploded view.

20

DETAILED DESCRIPTION OF THE INVENTION

In accordance with this invention, electricity is efficiently generated by a
25   compact system that will produce no smog products in the atmosphere. An overall description of the system of the present invention is first presented followed by a detailed description of each subsystem described with reference to the figures.

One power generation system aimed at solving the smog problem is disclosed in United States patent number 5,709,077, issued January 20, 1998, and
30   entitled "Reduced Pollution Hydrocarbon Gas Generator" (hereinafter, "the Beichel patent") which is incorporated herein by reference in its entirety. In the Beichel patent, high pressure liquid oxygen and fuel are separately delivered to a gas generator combustion chamber for combustion. After combustion, the mainstream gases pass through turbines where the thermal energy drives electrical
35   generators. The oxygen and fuel are not pre-mixed prior to being delivered to the combustion chamber.

The present invention uses the oxygen present in oxygen rich gas, not air, to burn the fuel (e.g., fossil fuel or a fuel including compounds containing carbon and hydrogen, at least one of the compounds in the fuel including the element carbon). The oxygen rich gas contains less nitrogen (e.g., the nitrogen has a mole

5   percentage of 10% or less, 1% or less, or even 0%) than is present in air and more oxygen (e.g., the oxygen has a mole percentage of 50% or more, 99% or less, or even 99% or more) than is present in air. The lower the nitrogen content of the oxygen, the lower the nitrous oxide emissions. The oxygen rich gas and the fuel are mixed prior to entering a combustion chamber where the mixture is ignited and

10   burned. In one embodiment, the oxygen is mixed with the fuel at higher than stoichiometric conditions such that there is slightly more oxygen than necessary to completely combust all of the fuel.

In describing the principles of the present invention, an exemplary embodiment is described by way of example. The exemplary embodiment is an

15   industrial power generation system emitting substantially zero pollution, having high efficiency (e.g., 70% or above), and generating net power of approximately 12.36 megawatts. The exemplary embodiment is an example only. One skilled in the art will recognize that many variations and modifications of the exemplary embodiment may be made within the scope of the invention.

20   The overall system is made up of four subsystems, the oxygen production system, the gas generation system, the main power system, and the auxiliary power system. Each subsystem contributes in its own way toward making the power generation system of the present invention a substantial improvement over the prior art with respect to efficiency and pollution. These subsystems and their

25   interrelation are now described.

A. OXYGEN PRODUCTION SYSTEM

Fig. 1 is a schematic drawing showing the overall industrial power

30   generation system 1 and the processes implemented in the system 1. Fig. 2 shows the oxygen production system 20 ("source of oxygen rich gas 20") which is one part of the overall power generation system 1 shown in Fig. 1. The oxygen production system 20 converts air into high pressure gaseous oxygen. In the exemplary embodiment in which 12.56 megawatts of power is produced, oxygen

35   production system 20 produces oxygen at 3.4 pounds per second ("lbm/s").

In the oxygen production system 20, air from, for example, the ambient environment, is initially dried and cleansed by passing through filter/drier 101. Filter/drier 101 may be a two stage system having a drier portion and a filter portion. The drier portion may include silica gel which absorbs most of the

5   moisture (H_2O) in the air. The filter portion removes particulates from the air. Fig. 1 shows that filter/drier 101 may contain a redundant parallel filter/drier 101a to allow the oxygen production system 20 to operate when servicing filter/drier 101 or to increase air intake capacity.

A low pressure compressor 102 receives and compresses the clean air to,

10   for example, 25 to 40 PSIA. A continuous membrane column 103 receives the compressed air and filters out most of the nitrogen (N_2). Argon, oxygen, H_2O, and CO_2 and only about 20% N_2 are allowed to pass to the outlet 104 of the continuous membrane column 103.

Continuous membrane columns are commonly available on the market and

15   are effective in extracting oxygen rich gases from air. Referring to Fig. 2, the left quadrants 103i and 103ii and the right quadrants 103iii and 103iv of the continuous membrane column 103 are separated by a membrane 103a comprising capillary or hollow fiber membranes. The flow is generally downward from the upper left quadrant 103i to the lower left quadrant 103ii and generally upward from the lower

20   right quadrant 103iii to the upper right quadrant 103iv. Air is fed between the upper and lower left quadrants. The air flows downward into the lower left quadrant. A negative pressure or vacuum is asserted by a low pressure compressor 105 such that gaseous permeation through the membrane 103a is facilitated. Since O_2 permeates faster than N_2, a disproportionately high volume of O_2 permeates

25   through the membrane 103a from quadrant 103ii to quadrant 103iii compared to N_2. The gases (such as nitrogen) that do not permeate through the membrane 103a, within the time allowed by the downward flow rate and length of the lower left quadrant 103ii, are exhausted out of the continuous membrane column 103 through discharge valve 103b at the lower portion of the lower left quadrant 103ii. The

30   oxygen rich gases flow upwards, through outlet 104, and into low pressure recirculation pump 105.

The pressure of the oxygen rich gases at the outlet 104 is approximately 15 PSIA. A low pressure recirculation pump 105 pumps the oxygen rich mainstream gases back up to approximately 25-40 PSIA. In order to increase the

35   steady state oxygen content of the oxygen rich gases passing through outlet 104, a portion (e.g., 50%) of the recompressed gases are recirculated back into the

continuous membrane column 103 into the upper left quadrant of the continuous membrane column 103. O_2 continues to permeate the membrane 103a from the oxygen rich gases in the upper left quadrant 103i into the upper right quadrant 103iv.

5   The remainder (e.g., 50%) of the oxygen rich gases are provided to a heat exchanger H.E. #1 which cools the gases from, for example, the range of approximately 200°F to 225°F to the range of approximately 100°F to 120°F. Heat exchanger H.E. #1, and all of the other heat exchangers described hereinafter, may be configured as a series of parallel platelets (commonly called a "platelet heat

10   exchanger") composed of, for example, copper. Although the size of the heat exchangers will depends on the power output of the system, platelet heat exchangers can be made small. Techniques for making such a heat exchanger are known and used in the aerospace industry.

Fig. 8A shows an exploded view of a platelet heat exchanger used in

15   accordance with the principles of the present invention. Fig. 8B shows the platelet heat exchanger of Fig. 8A in an unexploded view. Platelet heat exchanger 800 includes gas flow platelets 801, 803, and 805 interstacked with water flow platelets 802, 804, and 806. The upper surface of each platelet 801-806 defines a channel of flow for the gas or water. The upper surface may be patterned to define the

20   channels using conventional photoetch processes. As cooling water passes through the channels of a water flow platelet the water receives heat from the neighboring gas flow platelets and is converted to steam. As gas flows from left to right, the gas transfers heat to the cooling water.

The cooled gases are provided to a high pressure compressor 106 where the

25   gases are pumped to a high pressure of, for example, approximately 900 PSIA at a temperature of approximately 750°F. These high pressure gases are provided to a heat exchanger H.E. #2 where they are cooled from, for example, approximately 750°F to approximately 100°F to 120°F. The cool side of the heat exchanger H.E. #2 includes a water recirculation system.

30   The cooled high pressure gases then pass through a molecular sieve bed 107 such as those available on the market. The molecular sieve bed 107 extracts the H_2O and CO_2 from the gases so that no ice or dry ice forms at the cryogenic portion of the oxygen production system. Only argon, nitrogen, carbon dioxide and oxygen exist in significant amounts at the outlet 108 of the molecular sieve bed

35   107. The argon, nitrogen, carbon dioxide and oxygen mixture are provided to a heat exchanger H.E. #3 which cools the mixture from, for example, 100-120°F

down to approximately -60°F. This cool high pressure mixture is expanded
through an expansion turbine 109 where the temperature of the mixture is reduced
to a temperature below the freezing point of oxygen but above the freezing point of
argon and nitrogen (e.g., -295°F). The mechanical energy of the expansion turbine

5   109 is converted into electrical energy in generator 110, thereby improving the
efficiency of the process.

The two phase mixture from expansion turbine 109 is provided to a
distillation tower 111 where the liquid oxygen is separated from the gaseous argon
and nitrogen. The carbon dioxide, nitrogen and argon are either packaged for

10   consumer use or may be exhausted into the environment. The impact of
exhausting nitrogen and argon into the environment is negligible since argon and
nitrogen are components of air and do not contribute to smog, the greenhouse
effect, or acid rain. Furthermore, there are numerous commercial uses for carbon
dioxide, nitrogen, and argon. The liquid oxygen is provided to pump 112 where

15   the liquid oxygen is pumped to a high pressure of, for example, approximately
3600 PSIA. The work needed to pressurize the liquid oxygen is minimal
(approximately 50 horsepower for a liquid oxygen flow of 3.4 pounds/second of
liquid oxygen) compared to the work required to pressurize compressible gases.
Part of the liquid oxygen is stored in a liquid oxygen start tank 113 for starting up

20   the system.

The high pressure oxygen is provided back to heat exchanger H.E. #3
where the high pressure oxygen is heated to, for example, approximately 50°F into
the dense gaseous phase of oxygen. This heat for warming the oxygen is the heat
lost from the argon, nitrogen, and oxygen mixture from the molecular sieve bed

25   107. The warmed high pressure oxygen is passed through heat exchanger H.E. #1
where the high pressure oxygen is heated to approximately 80°F to 100°F. This
heat is taken from the low pressure oxygen, nitrogen, water, carbon dioxide, and
argon mixture passing through heat exchanger H.E. 1 in the opposite direction
from low pressure compressor 105. The high pressure oxygen is thus prepared to

30   be used with the gas generator 30 (Fig. 3).

It should be noted that there are many systems and ways of providing high
pressure oxygen. For example, oxygen is commercially available and need not be
extracted from air on site. While the oxygen production system described above
has many advantages, any source of high pressure oxygen may be used to provide

35   oxygen to the gas generator 30 (Fig. 3). Furthermore, oxygen generation system

20 may generate high pressure oxygen for purposes other than for use in a
combustion chamber.

B. GAS GENERATOR

5   Fig. 3 shows gas generator 30 of Fig. 1. Oxygen gas passes through line
162 to the mixing chamber 114 ("mixing unit 114"). For example, in the
exemplary embodiment, in order to produce 12.56 megawatts of power, the oxygen
gas is between 3400 and 3500 PSIA, between 60°F and 560°F, and at flow rate of
approximately 3.4 lbm/s. The other line 301 going to the mixing chamber 114
10   supplies high pressure steam. For example, in the exemplary embodiment, the
steam is at a pressure of between 3400 and 3500 PSIA, at a temperature between
560°F and 750°F, and at a flow rate of approximately 4.2 lbm/s. The steam is
mixed with the oxygen in the initial mixing chamber 114, which employs a series
of baffles 302 to perform the mixing process. In the exemplary embodiment, the
15   mixed gases have a pressure between 3400 and 3500 PSIA, a temperature between
510°F and 560°F, a flow rate of approximately 7.6 lbm/s, and mole percentages of
68.7 % H_2O and 31.3% O_2. Throughout this description an exemplary
embodiment is referred to for purposed of illustration. For clarity, Table 1 below
illustrates inlet and outlet flow rates, temperatures, pressures, and gas compositions
20   at various stages of the exemplary embodiment industrial power generation system
1 as determined by simulation. Although Table 1 shows specific flow rates that
correspond to a simulated 12.36 megawatt system. These flow rates may be scaled
for other power outputs.

location	Temp. (°F)	Pressure (PSIA)	Flow Rate (lbm/s)	Mole Percentages (%)				
				O_2	H_2O	CH_4	CO_2	OH
162	60-560	3400-3500	3.4	100				
301	560-750	3400-3500	4.2		100			
114 outlet	560-750	3400-3500	7.6	31.3	68.7			
303 fuel inlet	80	3400-3500	0.5			100		
116	560-750	3400-3500	8.1	28.7	62.9	8.4		
118 outlet	3200	3300	8.1	11.7	79.3		8.4	0.6
119	3000	3200	8.45	11.1	80.3		7.9	0.6
30 outlet	2000	3100	8.69	10.8	81.0		7.7	0.5
126 outlet	1585	1000	8.69	10.8	81.0		7.7	0.5
131 fuel inlet	80	1000	0.081			100		
131 inlet	1560	1000	8.771	10.6	80.0	1.2	7.6	0.5
131 outlet	2000	1000	8.771	8.3	82.8		8.9	
132 outlet	1475	245	8.771	8.3	82.8		8.9	
133 fuel inlet	80	245	0.115			100		
133 inlet	1475	245	8.886	8.1	81.4	1.7	8.7	
133 outlet	2000	245	8.886	4.7	84.9		10.4	
134 outlet	1340	60	8.886	4.7	84.9		10.4	
135 fuel inlet	80	60	0.118			100		
135 inlet	1340	60	9.004	4.6	83.4	1.7	10.3	
135 outlet	2000	60	9.004	1.1	86.9		12.0	
136 outlet	1590	20	9.004	1.1	86.9		12.0	
HE #5 outlet	230	20	9.004	1.1	86.9		12.0	

Table 2

The mixed gases then go to a second mixing chamber 303 ("mixing unit 303") where fuel, such as methane gas, is added from a source of fuel 350 (Fig. 1). In the exemplary embodiment, methane gas is added at a pressure between 3400 and 3500 PSIA, at a temperature of approximately 80°F, and at a flow rate of

5   approximately 0.5 lbm/s. This chamber 303 (Station 4) contains conventional high temperature Raschig rings 304 to promote turbulence and mixing of the fuel, oxidizer and steam to produce a very uniform mixture at the injector inlet chamber 307. A control valve 305 is located between the mixing chamber 303 and the injector inlet chamber 307 at Station 5. Control valve 305 is spring loaded to

10   control the amount of flow entering the combustion chamber 118. Control valve 305 also serves as an emergency shut down should something happen downstream that might result in a rapid increase or reduction in chamber pressure. When a shut down occurs for any reason, whether automatically due to an emergency situation, or whether manually due to a planned shut down, a fuel supply valve 303a

15   supplying fuel to mixing chamber 303 is automatically closed while a nitrogen purge value 303b supplying nitrogen to mixing chamber 303 is opened. Thus, mixing chamber 303, gas generator 30 and ultimately the entire system 1 can be purged of inflammable gases during shut down. A second purpose of the nitrogen purge is to assist in starting up the unit by cooling the mainstream gases until the

20   diluent steam system is fully operational.

The mixture of fuel, oxidizer and steam is introduced into the combustion chamber 118 through a series of small circular injection ports 309 provided in an injector plate 116. Injector plate may be composed of, for example, stainless steel. In the exemplary embodiment, the mixture has at flow rate of 8.1 lbm/s and mole

25   percentages of 62.9% H_2O, 28.7% O_2 and 8.4% CH_4. The circular injection ports 309 can be sized to provide adequate injection velocity so as to prevent back flash into the upstream injection. In other words, the ports 309 should be sized so that the injection velocity of the mixed gases is greater than the flame propagation velocity. The dimensions of ports 309 will depend on the mixture composition and

30   temperature desired and can be empirically determined. During shut down, nitrogen purge gas is injected into the system to purge the system of inflammable gases. This purge nitrogen passes through gas generator 30 and main power generation system 40 and is eventually recovered in the distillation tower 148 in the oxygen production system 20 just as the CO_2 generated by the combustion

35   process is recovered as described in detail hereinafter.

Combustion takes place just downstream of the injector face 306 in
combustion chamber 118. The pre-mixing of the oxygen, fuel, and steam prior to
injection into combustion chamber 118 assures complete combustion of the gases
in the combustion chamber 118, thereby improving the combustion efficiency. An

5   ignition plug 117 ("igniter 117"), at Station 6, is placed at the center of the
injection plate 116, in one embodiment, and is used to initiate the combustion
process. The walls of combustion chamber 118 are cooled by water passing
through a series of platelets 308 that make up the chamber wall. This form of
cooling, known as transpiration cooling, cools the walls of the chamber 118 to a

10   temperature (e.g., 700°F to 900°F) well below the melting point of the material
(e.g., stainless steel) making up the chamber wall. However, even though the walls
of chamber 118 are cooled, transpiration cooling has only a negligible cooling
effect on the mainstream gases.

The transpiration cooling process is described in more detail with regard to

15   Figs. 6A and 6B. Fig. 6A is an exploded isometric view of two flat ring-shaped
platelets 610 and 620 which are part of the series of platelets 308. Platelets 610
and 620 may be composed of, for example, stainless steel. Platelets 610, 620 and
all the other platelets of the series of platelets 308 are stacked together. Grooves
are formed in at least one of the facing surfaces to allow water to pass along the

20   grooves and cool the platelets such as platelets 610 and 620. The stack of platelets
308 forms the wall of combustion chamber 118.

Fig. 6B is a detailed exploded isometric view of portion 6B of Fig. 6A.
Fig. 6B shows that each platelet 610 and 620 has a grooved surface 622 with open
channels 624 formed therein by, for example, etching. The open channels 624 run

25   from the outer diameter to the inner diameter. Platelets 610 and 620 may be, for
example, 0.010 inches thick and have ridges having a cross section of, for example,
0.005 wide by 0.005 deep. Platelets 610 and 620 are stacked together such that
facing surfaces of adjacent platelets are in physical contact thereby forming
channels 624 of platelet 610. The other platelets of the series of platelets 308 have

30   similar channels.

A small total amount of water (e.g., approximately 0.1 lbm/s) from
reservoir 321 (Fig. 3) passes through channels 624 and enters the combustion
chamber 118. Heat from within the combustion chamber 118 transfers into the
series of platelets 308 such that the platelets 308 heat the water within channels

35   624 to form steam. The water within the channels 624 absorbs heat to cool

platelets 308 to well below the melting point of the material making up the platelets 308.

Referring again to Fig. 3, the initial combustion may take place in an oxidizer rich atmosphere, which means there is more oxygen present in the mixture
5   than is required to burn all the fuel introduced into the initial combustion process. Reasons for this will become clear later in the discussion of the reheaters. In the exemplary embodiment, the combustion gases from chamber 118 are at 3200°F and 3300 PSIA and include mole percentages of 79.3% H_2O, 11.7% O_2, 8.4% CO_2, and 0.6% OH with traces of CO. In the exemplary embodiment, these combustion
10   gasses require further cooling down prior to entering the turbines which contain iron or steel. Alternatively, cooling down may not be required if ceramic materials are used in the turbines immediately downstream from chamber 118.

An extension 320 is added to the initial chamber 118 where coolant water is injected from injectors 120a and 120b and mixed with the mainstream gases at
15   Station 8. In the exemplary embodiment, coolant water is injected at approximately 3300 PSIA, 150°F, and 0.35 lbm/s. This water injection provides some initial temperature reduction (e.g., down to approximately 3000°F in the exemplary embodiment) in the combustion gases to make the gas temperature compatible with the materials (e.g., copper in the exemplary embodiment) used in
20   heat exchanger H.E. #4. Although copper has a melting point below the temperature (e.g., 3000°F) of the hot gases provided to heating exchanger H.E. #4, the copper remains structurally sound because the copper platelets are being continuously cooled by the cool water provided to the cold side of the heat exchanger H.E. #4.

25   Before the coolant water is injected into the mainstream gases, the coolant water is injected into a cooling reservoir 321 provided within the walls of extension 320 which cools the walls of the extension 320 to well below the melting point of the materials (e.g., steel) that make up the walls of extension 320. Thus, the walls of extension 320 remain structurally sound even if the mainstream gases
30   are at a temperature above the melting point of the material (e.g., steel) making up the walls of the extension 320.

A solid concave disc 119 (i.e., splash plate 119 made of, for example, copper) is placed in the center of the mainstream gases to catch the H_2O rich gases just downstream of the injection ports 120a and 120b. In the exemplary
35   embodiment, these H_2O rich gases are at approximately 3300 PSIA, 3000°F, and 8.45 lbm/s with mole percentages of 80.3% H_2O, 11.1% O_2, 7.9% CO_2, 0.6% OH

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and traces of CO. Splash plate 119 is kept from melting due to the cooling effect of the cooling water splashing on its surface. Due to its concave shape, splash plate 119 throws the H_2O rich gases outwards around the ends of the splash plate 119 to assist in thoroughly mixing the injected H_2O with the other mainstream

5   gases. The water injection system and splash plate 119 lower the temperature of the mainstream gases while adding more mass flow for driving the downstream turbines. Although the use of splash plate 119 has mixing efficiency advantages, other in line mixing structures may be used. A mixing structure may even be completely omitted with some possible sacrifice in mixing efficiency.

10   Two ways to increase turbine output power are to increase turbine inlet gas temperatures and/or increase the mass flow to the turbine stages. Inlet gas temperature is limited by the materials used in the turbines such as steel. Adding water increases the mass flow and lowers the gas temperature making this a very acceptable trade off in the overall power output of the turbine stages. This is

15   particularly significant in that the molecular weight of the steam is less than that of the mainstream gases and a low molecular weight gas will produce more horsepower per unit mass than a high molecular weight gas. By adding water in stages, the temperature of the mainstream gases is reduced incrementally over the length of the gas generator.

20   In the heat exchanger H.E. #4, the temperature of the mainstream gases is lowered again to an intermediate temperature prior to entering the turbines. In the exemplary embodiment, this intermediate temperature is approximately 2110°F. Cooling water is provided to the cold side of heat exchanger H.E. #4. In the exemplary embodiment, this cooling water is provided at a temperature of

25   approximately 80°F and 4.2 lbm/s. In heat exchanger H.E. #4, this cooling water is heated up to steam (e.g., at approximately 750°F). This steam is mixed with oxygen in mixing chamber 114 (Fig. 3). Thus, the heat lost by the mainstream gases in heating this steam is not lost in the overall system. In the heat exchanger H.E. #4, the temperature of the mainstream gases is lowered further to approach

30   the temperatures that can be handled by the turbines of primary turbine stage 126 (Fig. 4) without sacrificing the output power capability of the system. In the exemplary embodiment, these mainstream gases are at approximately 3100 PSIA and the temperature is lowered to approximately 2110°F.

        The region downstream of the heat exchanger H.E. #4 has an additional

35   water injection Station 9 having injectors 122a and 122b (Fig. 3). The additional water injection station is used to control the input temperature to the primary

turbine stage 126 to design conditions within ±10°F by sensing the inlet
temperature to the primary turbine stage 126 (Fig. 4), Station 10, and controlling
the amount of water injected at injectors 122a and 122b based on the temperature
measurement. For example, the desired inlet temperature for primary turbine stage

5   126 is set, in the exemplary embodiment, for 2000°F. The amount of water
injected is increased when the temperature climbs above 2000°F and is decreased
when the temperature falls below 2000°F. Again a splash plate 121 (Fig. 3), which
may be similar to splash plate 119, is positioned just downstream of injectors 122a
and 122b, and is employed to mix the water with the mainstream gases from

10   extension 320 prior to exiting the gas generator 30.

Although methane is described as being a fuel for the above power
generation system, natural gas may be used instead. Natural gas may contain
significant quantities of hydrogen sulfide which, when heated in an oxygen rich
environment, forms sulfur dioxide. This sulfur dioxide, if emitted into the

15   environment, contributes to acid rain. The sulfur dioxide byproduct may be
eliminated by injecting calcium rich lime water through or near the injectors 122a
and 122b. The calcium of the lime water combines with the sulfur in the natural
gas to form calcium sulfate, a byproduct which does not contribute to acid rain, the
greenhouse effect, or smog. The calcium sulfate passes with the mainstream gases

20   and accumulates in the storage tank 154 with water. As water is a byproduct of the
combustion process, water (with calcium sulfate) is drained from storage tank 154
to prevent water overflow in the condenser/collector 148. Thus the calcium sulfate
is drawn from the industrial power generation system 1. The sulfur dioxide
byproduct can also be eliminated using conventional sulfur filtering of the natural

25   gas prior to introduction into the gas generator 30.

Output mainstream gases of the gas generator 30 then go to the main power
system 40 (Fig. 4) where the potential energy in the gas stream is converted into
mechanical energy in the turbine stages 126, 132, 134, and 136 and then into
electrical energy in the generators 128 and 137. In the exemplary embodiment,

30   these output mainstream gases are at approximately 3100 PSIA, 2000°F, and 8.69
lbm/s having a mole percentage of 81.0% H_2O, 10.8% O_2, 7.7% CO_2, 0.5% OH.
Although a 0.5% mole percentage of OH and minute traces of CO are
approximated in the simulation, OH and CO will, in practice, be combusted in the
gas generator 30 leaving only H_2O, O_2, and CO_2.. If any OH or CO molecules are

35   present at the outlet of gas generator 30, then combustion is incomplete. A
conventional infrared sensor at the outlet of gas generator 30 can detect the

molecules OH and CO and use a conventional feedback mechanism to add more oxygen to gas generator 30 so that all OH and CO molecules are completely combusted within gas generator 30. A similar feedback system can be provided at each reheater 133 and 135 to ensure that enough oxygen is introduced to

5   completely combust the fuel.

The gas generator 30 (Fig. 3) may be made very small. For example, in the exemplary embodiment, gas generator 30 need only have an outside diameter of approximately 12 inches, an inside diameter of approximately 8 inches, and a length of approximately 8 feet.

10

C. MAIN POWER GENERATION SYSTEM

The main power system 40 for generating electrical power is shown in Figure 4. The hot high pressure mainstream gases exiting gas generator 30 expand within a primary (first stage) turbine stage 126 (or "radial inflow turbine 126") to

15   produce mechanical energy. In the exemplary embodiment, radial inflow turbine 126 receives 2503 horsepower of energy from the mainstream gases. This mechanical energy ("brake horsepower") of turbine stage 126 is converted to electrical energy in electrical generator 128. In the exemplary embodiment, the electrical generator 128 efficiency is approximately 98.5 % and thus the electrical

20   energy produced by the 2503 horsepower is 1.84 megawatts (2503 hp * (746 watts / hp) * (0.000001 megawatts / watt) * 0.985) which represents 14.6 % of the total output power of 12.56 megawatts.

The mainstream gases exit radial inflow turbine 126 and enter reheater 131. In the exemplary embodiment, the mainstream gases exiting radial inflow turbine

25   126 are at approximately 1000 PSIA and 1585°F. Primary turbine stage 126 may be a single stage radial inflow turbine that operates at approximately a 3/1 pressure ratio with a design inlet temperature (e.g., 2000°F) and pressure (approximately 3100 PSIA).

The high inlet pressure allows for a very compact turbine 126. The

30   combination of flow and pressure ratio (3/1) is such that this turbine operates in the specific speed range for radial inflow turbines, so that a relatively high efficiency can be expected. A radial inflow turbine runs smoothly and is relatively uninfluenced by minor fluctuations in inlet flow. Thus, it will drive generator 128 stably and smoothly.

35   Reheater 131 is introduced between the radial inflow turbine 126 and the high pressure secondary turbine stage 132 (or "axial turbine stage 132"). An

embodiment of reheater 131 is shown in Fig. 7. Reheater 131 may be composed of a single hollow tube 600 made of, for example, stainless steel, copper or other material of high heat transfer coefficient, which is bent to form a solinoidal shape having an inlet 601, solinoidal middle portion 603 and an outlet 602. Reheater 131

5   receives fuel at inlet 601. The fuel travels through hollow tube 600 and is combined with fuel at fuel inlet 604. In the exemplary embodiment, this fuel is methane at approximately 1000 PSIA, $80°F$, and 0.081 lbm/s. Since the mainstream gases (e.g., at a temperature of approximately $1585°F$) are sufficiently above the ignition temperature of the fuel (e.g., methane) but well below the

10   melting point of stainless steel, the fuel will spontaneously ignite in the presence of the oxidizer rich mainstream gases and the hollow tube 600 will not melt.

As the combusting mixture of fuel and mainstream gases travels through the solinoidal middle portion 603 of the hollow tube 600, the bends in the middle portion 603 cause mixing, and thus efficient combustion, of the fuel and

15   mainstream gases. The outlet 602 is made sufficiently far from the inlet 601 in terms of mainstream gas running distance such that complete combustion occurs prior to entering the next turbine stage 132.

In other embodiments, the temperature of the mainstream gas exhausted from turbine 126 is not enough to spontaneously ignite the fuel in which case an

20   ingiter is, of course, necessary in reheater 131. This combustion of the fuel/mainstream gas mixture in reheater 131 heats the mainstream gases exiting reheater 131 to bring the mainstream gas temperature at the inlet to the axial turbine stage 132 to design conditions. In the exemplary embodiment, the fuel/mainstream gas mixture entering reheater 131 is at approximately 1000 PSIA,

25    $1560°F$, and 8.771 lbm/s having mole percentages of 80.0% H_2O, 10.6% O_2, 1.2% CH_4, 7.6% CO_2, 0.5% OH, and traces of CO. After combustion, the mainstream gases exiting reheater 131 are at approximately 1000 PSIA, $2000°F$, and have mole percentages of 82.8% H_2O, 8.3% oxygen, 8.9% carbon dioxide, and minute traces of HO and CO. The amount of fuel needed to increase the temperature to design

30   conditions (e.g., $2000°F$) is so small weightwise, that the performance of the secondary turbine stages 132, 134 and 136 is enhanced very efficiently.

A fairly small amount of fuel (e.g., methane at 0.081 pounds/second) is required to raise the mainstream gas temperature back up to inlet temperature design conditions for turbine stage 132. Thus, additional reheaters 133 and 135 are

35   provided before turbine stages 134 and 136, respectively. Raising the turbine output temperature by $500°F$ will produce a 23% increase in horsepower for the

next stage assuming identical pressure ratios across the stages. Again this is a cumulative effect in that successive stages 134 and 136 are influenced by the heat addition in the initial reheater stage 131 tending to make the entire process more efficient.

5   The reheaters 131, 133 and 135 are made up of conventional spiral tube shaped mixers. The inside diameter of the tube may be approximately five inches for a 12.36 megawatt system but may be scaled according to the power output. As the mainstream gases and the added fuel are forced through the hollow coiled tubes, the mainstream gases experience shear which swirls and mixes the

10   combusting gaseous mixture as the mixture proceeds through the reaction chamber. The spiral tubes are made long enough that the mainstream gases have sufficient residence time for the fuel to completely burn. The stay time, and thus the length of the tubes, is a function of the flow rate, combustion temperature, and can be conventionally determined.

15   Each of the secondary turbine stages 132, 134 and 136 may consist of three axial turbines in series as the pressure ratio across an individual axial turbine should be approximately 1.6/1 or less for good turbine efficiency. Three of such axial turbines for each turbine stage 132, 134 and 136 would produce a pressure ratio of approximately 4/1 ($\cong$1.6x1.6x1.6) for each turbine stage 132, 134 and 136.

20   The pressure ratio for each individual axial turbine can be greater than 1.6, but a penalty is paid in overall efficiency as the pressure ratio goes up since most axial turbines are designed for a pressure ratio of approximately 1.6. "Pressure ratio" is defined as inlet pressure over the discharge pressure for a specific turbine or turbine stage. For example, the inlet pressure to the high pressure secondary

25   turbine stage 132 is approximately 1000 PSIA and the discharge pressure is approximately 245 PSIA resulting in an approximately 4/1 pressure ratio. The temperature of the mainstream gases is reduced from approximately 2000°F to 1475°F across turbine stage 132. Three axial turbines in series would be used to make up the turbine stage 132.

30   The mainstream gases from reheater 131 expand within turbine stage 132 to produce mechanical energy in turbine stage 132 which is converted to electrical energy in generator 137. In the exemplary embodiment, the mainstream gases at 1000 PSIA and 2000°F expand down to 245 PSIA and 1475°F within turbine stage 132 to produce 3209 horsepower of mechanical energy which is converted to 2.36

35   megawatts of electrical power assuming a turbine stage 132 efficiency of 98.5%.

This 2.36 megawatts represents 18.8% of the total output power of 12.56 megawatts.

The mainstream gases which exit this turbine stage 132 go to the second reheater 133 of the same design as reheater 131, where the mainstream gas
5   temperature is raised back up to the design inlet temperature of turbine stage 134 by injecting more fuel into the mainstream gases. In the exemplary embodiment, the temperature of the 245 PSIA mainstream gases is raised to approximately 2000°F by adding approximately 0.115 lbm/s of CH_4. In the exemplary embodiment, the fuel/mainstream gas mixture has a flow of 8.886 lbm/s and mole
10   percentages of 81.4% H_2O, 8.1% O_2, 1.7% CH_4, 8.7% CO_2, and traces of OH and CO. After combustion, the mainstream gases have mole percentages of 84.9% H_2O, 4.7% O_2, 10.4% CO_2 and traces of OH and CO.

The mainstream gases from reheater 133 expand within the second turbine stage ("intermediate pressure secondary turbine stage 134") to produce mechanical
15   energy in turbine stage 134 which is converted to electrical energy in generator 137. In the exemplary embodiment, the mainstream gases at 245 PSIA and 2000°F expand down to 60 PSIA and 1340°F within turbine stage 134 which may contain three axial turbines in series. This expansion produces approximately 3270 horsepower of mechanical energy which is converted to 2.40 megawatts of
20   electrical power assuming a turbine stage 134 efficiency of 98.5%. This 2.40 megawatts represents 19.1% of the total output power of 12.56 megawatts.

The mainstream gases which exit this turbine stage 134 go to the third reheater 135 of the same design as reheater 131, where the mainstream gas temperature is raised back up to the design inlet temperature of turbine stage 136
25   by injecting more fuel into the mainstream gases. In the exemplary embodiment, the temperature of the 60 PSIA mainstream gases is raised to approximately 2000°F by adding approximately 0.118 lbm/s of CH_4. In the exemplary embodiment, the fuel/mainstream gas mixture has a flow of 9.004 lbm/s and mole percentages of 83.4% H_2O, 4.6% O_2, 1.7% CH_4, 10.3% CO_2, and traces of OH and
30   CO. After combustion, the mainstream gases have mole percentages of 86.9% H_2O, 1.1% O_2, 12.0% CO_2 and traces of OH and CO.

The mainstream gases from reheater 135 expand within the third turbine stage ("low pressure secondary turbine stage 136") to produce mechanical energy in turbine stage 136 which is converted to electrical energy in generator 137. In
35   the exemplary embodiment, the mainstream gases at 60 PSIA and 2000°F expand down to 20 PSIA and 1590°F within turbine stage 134 (which typically contains

three axial turbines in series). This expansion produces approximately 2678 horsepower of mechanical energy which is converted to 1.97 megawatts of electrical power assuming a turbine stage 134 efficiency of 98.5%. This 1.97 megawatts represents 15.7% of the total output power of 12.56 megawatts.

5   After exiting turbine stage 136, the mainstream gases now enter a post treatment phase, where heat is extracted from the mainstream gases and utilized in an auxiliary power system 50 (Figs. 1 and 5) for further electrical power generation.

10   D. AUXILIARY POWER GENERATION SYSTEM
         The auxiliary power system 50 (Fig. 5) includes an auxiliary fluid circuit (e.g., a water/steam circuit) and is shown in Figure 5. The exhaust gases from turbine stage 136 in main power system 40 have very little potential energy, as the pressure has been reduced to 20 PSIA in the exemplary embodiment. However,

15   the exhaust gases still possess considerable thermal energy even after passing through turbine stages 126, 132, 134 and 136 because of the reheating in reheaters 131, 133 and 135. In the exemplary embodiment, for example, the mainstream gas exiting turbine stage 136 is approximately 1590°F. The thermal energy content of the mainstream gas is further enhanced by the fact that approximately 86.9% of the

20   mainstream gas is steam which when condensed as water provides a significant heat source for the auxiliary steam power system 50.
         Post treatment of the power system's effluent consists of taking mainstream gases from mainstream power system 40 through a heat exchanger H.E. #5 to reduce the gas temperature. In the exemplary embodiment, the 20 PSIA

25   mainstream gases are cooled from 1590°F to 230°F which results in a heat loss rate of 19,710,000 Btu/hr from the mainstream gases. This cooled effluent then passes through a heat exchanger H.E. #6 in which the steam of the mainstream gas is condensed into water. In the exemplary embodiment, this condensation and cooling results in a heat loss of approximately 23,900,000 Btu/hr for a total heat

30   loss in heat exchangers H.E. #5 and H.E. #6 of 43,610,000 Btu/hr.
         During this cooling process, CO combines with O_2 form CO_2 and OH loses some oxygen atoms to form H_2O. Thus, in the exemplary embodiment, the effluent from main power system 40, having mole percentages of 86.9% H_2O, 1.1% O_2, 12.0% CO_2 and traces of OH and CO, results in a cooled effluent

35   containing only H_2O, CO_2, and O_2. Other element mole percentages are negligible. The two-phase mixture (e.g., only H_2O is in the liquid phase) in the heat exchanger

H.E. #6 goes to a scrubber 148 (Fig. 1). The excess water from the scrubber 148
(Fig. 1) is sent to storage 154 (Figs. 1 and 5) where a portion is used for make up
water for the auxiliary power system 50, a portion is bled off to compensate for the
H_2O produced in the combustion process, and the remainder is recycled back into
5   the gas generator 30 via H_2O pump 151 that raises the water pressure to
approximately 3500 PSIA. The high pressure water from pump 151 passes
through heat exchanger H.E. #7 to raise the temperature to approximately 200°F
prior to returning to injectors 120a and 120b in the gas generator 30.

        H_2O from an auxiliary flow circuit 502 is heated to the turbine inlet
10   temperature (e.g., 1200 °F) of auxiliary steam turbine stage 142 by the turbine
exhaust effluent from the primary power generation system 40 passing through
heat exchangers H.E. #5 and #6. The evaporator side of the second exchanger H.E.
#6 has water entering, for example, at approximately 150°F pumped to a pressure
of, for example, approximately 1000 PSIA by H_2O pump 152. The output from
15   exchanger H.E. #6 is low temperature steam which is delivered to an exchanger
H.E. #5 that superheats the steam to, for example, a temperature of approximately
1200°F at a pressure of approximately a 1000 PSIA. In the exemplary
embodiment, the 43,610,000 Btu/hr of heat from the mainstream gases exhausted
from main power system 40 is transferred to the steam of the auxiliary power
20   system 40.

        The performance of evaporation and condensation in two separate heat
exchanges is a very efficient means of transferring heat. The surface area required
for latent heat transfer in heat exchanger H.E. #6 is much smaller than the surface
area needed for sensible heat transfer in H.E. #5 even though the total latent heat
25   transferred in heat exchanger H.E. #6 is greater than the sensible heat transferred in
heat exchanger H.E. #5.

        This superheated steam then travels to auxiliary turbine stage 142, which
converts a percentage of the heat transferred to the steam in heat exchangers H.E.
#5 and H.E. #6 into mechanical energy. In the exemplary embodiment, the
30   auxiliary turbine stage converts 13,900,000 Btu/hr of the 43,610,000 Btu/hr of heat
received by the steam in heat exchangers H.E. #5 and H.E. #6 into 5459
horsepower assuming a turbine stage 142 efficiency of 31.87%. This 5459
horsepower of the auxiliary turbine stage 142 efficiency is converted into 4.01
megawatts of electrical power in generator 137 assuming a generator efficiency of
35   98.5%. This 4.01 megawatts represents 31.4% efficiency for auxiliary turbine

stage 142 together with generator 137 and represents 31.92% of the total output
power of 12.56 megawatts.

Auxiliary turbine stage 142 may be two radial inflow turbines in series,
which power either the main electrical power generator 137 or a separate generator
5   system that stands alone. Effluent from the auxiliary turbine stage 142 is steam at,
for example, a temperature of approximately 230°F and a pressure of
approximately 10 PSIA. The steam is then condensed to water in heat exchanger
H.E. #7 and returned to heat exchangers H.E. #5 and #6 by H_2O pump 152.

The following Table 2 summarizes the contribution of each turbine stage to
10   the 12.56 megawatts of electrical power generation in the preferred embodiment.

Stage	Mechanical Energy (SHP)	Electrical Power Contribution	Percentage of 12.56 megawatts
126	2503	1.84	14.6
132	3209	2.36	18.8
134	3270	2.40	19.1
136	2678	1.97	15.7
142	5459	4.01	31.9
total	17119	12.56	100.0

Table 2

15   The reasons for the high contribution of turbine stage 142 are (1) the reheat
processes keep the thermal energy content of the mainstream gases quite high until
fully utilized in the heat exchangers H.E. #5, H.E. #6 and H.E. #7 in the latter stage
of the process, (2) the latent heat content of the mainstream gases and the auxiliary
steam are used to promote maximum utilization of heat content in both streams that
20   pass through heat exchangers H.E. #5 and H.E. #6, and (3) high pressure system
capability is significantly enhanced by pumping water rather than compressing
steam or any other diluent gases for the combustion process (e.g., carbon dioxide
and nitrogen).

25

E. CONCLUSION

The power generation system of the present invention offers the highest efficiencies available anywhere at this time, emits essentially zero pollution, and is very compact. Oxygen and fuel (e.g., methane or natural gas) are combusted to

5   provide energy while steam may act as a heat absorbing agent. The system is more compact than conventional systems because the gas generators and high pressure turbines can be made smaller for a given power output due to the high pressure operation. It is estimated that using the principles of the present invention, the industrial power generation system 1 (Fig. 1) can be made approximately 30%

10   smaller (for a 12.56 megawatt output) than the conventional industrial power generation systems of equivalent power output.

Elimination of the nitrogen from the combustion process means that substantially no smog is produced by this power generation system. Combination of the sulfur with the calcium of the injected lime water means that substantially no

15   acid rain is ever caused by this power generation system.

If operated stoichiometrically with no heat adsorbing agent such as nitrogen, just the proper amount of oxidizer is provided to consume all the fuel. In this stoichiometric condition, the gas temperatures in the combustion chamber 118 are as high as they can get (e.g., over 6000°F). The chamber walls cannot typically

20   handle this high temperature. In the power generation system 1 (Fig. 1) of the present invention, water/steam is added to the combustion process to keep the combustion temperature low enough (e.g., 3200°F) to not damage the combustion chamber 118.

The premixed gases from the injector cavity are transmitted through the

25   injector plate 116 through a series of injector ports 309 uniformly distributed across the injector plate 116. An igniter 117 (e.g., an ignition plug) is located at the center of the injector face 306. Combustion takes place at a high pressure such as approximately 3300 PSIA. This high pressure has not previously been used in the power industry. Of course, other appropriate high pressures may also be used.

30   The combustion chamber 118 in the power generation system 1 of the present invention is cooled using, for example, transpiration cooling with water/steam injected through the wall similar to that employed in a liquid rocket engine. Photo-etched, annular shaped, stainless steel wafers 610 and 620 (Figs 6A and 6B) containing minute channels 624 are used to distribute the coolant through

35   the wall to maintain a reasonably cool temperature (e.g., approximately 800°F to 900°F) for the wall of combustion chamber 118. Additional water is injected at

injectors 120a and 120b and mixed into the mainstream just downstream of the main combustion chamber 118. The heat exchanger H.E. #4 extracts heat from the mainstream gases and inputs heat into the steam being delivered to the premix chamber 114 (i.e., "mixer 114"). The high temperature of the steam in the premix

5   chamber 114 promotes mixing of the steam with the oxygen. When the mixed steam and oxygen is forced into chamber 303 and mixed with fuel in chamber 303, the reaction time in the combustion chamber 118 9 is reduced allowing combustion to take place almost instantaneously.

Second water injectors 122a and 122b and splash plate 121 are located just

10 downstream of the heat exchanger H.E. #4. The amount of water injected at this station is controlled by a thermocouple ("temperature sensor 180" in Fig. 1) at the inlet of the primary turbine stage 126. The inlet temperature to turbine stage 126 is set at a prescribed design condition and the amount of water injected in extension 320 is controlled to maintain this condition plus or minus ten degrees Fahrenheit.

15   A radial flow inlet turbine (i.e., turbine stage 126) serves as the first phase of the main power generation system 40. A radial inflow turbine was selected because the high inlet pressure (approximately 3000 PSIA) and relatively low speed (3600 RPM) require a low specific speed turbine for reasonable operating efficiency and compact sizing. Axial turbines perform better at high specific

20 speeds while radial inflow turbines perform well at low specific speeds.

Reheater 131 (Fig. 4) is installed between the primary turbine stage 126 and the high pressure secondary turbine stage 132 to heat the mainstream gases prior to entering to entering turbine stage 132. Another reheater 133 is provided downstream of turbine stage 132 to reheat the mainstream gases prior entering the

25 intermediate pressure turbine stage 134. This stage 134 is followed by a third reheater 135 where the fuel added is almost enough to use up the excess oxygen from the original combustion mixture. Therefore the exhaust gas from this reheater 135 will have trace amounts of unburned hydrocarbons and only a small amount of oxygen at the design inlet temperature for the next turbine stage 136. In the

30 exemplary embodiment, the combined effect of the reheaters 131, 133 and 135 on the overall power generated is a 10% increase after the high pressure secondary turbine stage 132, a 27% increase after the intermediate pressure secondary turbine stage 134, and a 42% increase after the low pressure secondary turbine stage 136 (all compared to the power generated by just the primary turbine stage 126). These

35 results illustrate the cumulative effect of the reheaters which increase the overall power output of the main power system 40 by a substantial margin.

Following the turbine stages 126, 132, 134 and 136, most of the pressure in the mainstream gases has been dissipated in driving turbines. However, the mainstream gases are still relatively hot. Auxiliary steam turbine stage 142 makes system 1 (Fig. 1) a combined cycle system. The heat from the mainstream gas

5   exiting the turbine stage 136 is transferred to an auxiliary stream of steam in heat exchangers H.E. #5 and #6. The resulting steam is then sent to steam turbine 142 for additional power generation. The steam turbine 142 is part of a closed loop system where the steam used to drive steam turbine 142 is cooled and condensed in heat exchanger H.E. #7 by the water recycled to the combustion chamber 118.

10   After pumping up the H_2O to the pressure required to drive the auxiliary turbine stage 142, the water is evaporated and superheated by the primary gas stream exhausted from main power system 40. Here again, the reheaters 131, 133 and 135 from the main power system 40 increase the amount of energy that can be retrieved by and used in the auxiliary steam turbine 142. In the exemplary embodiment, the

15   auxiliary power system 50 accounts for approximately 30% of total power output of system 1.

In the exemplary embodiment, the effluent from main power system 40 has mostly H_2O in the liquid phase and CO_2 in the gaseous phase. This effluent empties into a separator tank 148 where the water is drained off. Most of the water

20   is sent back to the gas generator 30 through pump 151 and heat exchanger H.E. #7, some is used for make-up in the auxiliary steam power system 50 and the remainder becomes a worthwhile product for use as needed. Gas from the separator 148 is primarily CO_2 with some O_2 (if O_2 was oversupplied from the oxygen generation system 20) The CO_2 and O_2, may be separated and sold

25   commercially or used as useful products. In one embodiment, the amount of oxygen supplied by oxygen production system 20 is lowered so that there is no extra O_2 left in the effluent. In that case, only CO_2 is present in the gaseous phase in separator 148. When all the byproducts of the industrial power generation system 1 are utilized as products, the system is a substantially closed loop system

30   where relatively little, if any, pollution is returned to contaminate the environment.

The system of the present invention can be adapted to modify an existing gas generator power plant using existing turbines, generators, pumps, and any gas separating equipment. Existing technology for making oxygen from air would be incorporated in the plant as well as an existing steam power generation package.

35   Nitrogen and argon recovery would come from existing oxygen production systems, as would carbon dioxide recovery. Only the mixing chambers, the

combustion chamber, heat exchangers, and reheaters would necessarily have to be fabricated to suit the modified process.

In one embodiment, the oxygen is combined with fuel at a stoichiometric ratio before combustion in chamber 118. Oxygen is then supplied separately to the
5   reheaters 131, 133 and 135 because there is no excess oxygen at the outlet of the gas generator 30. The quantity of oxygen and fuel input to the reheaters 131, 133 and 135 depends on how much unburned fuel or excess oxygen is present at the outlet of gas generator 30.

Although a 12.36 megawatt industrial power generation system is described
10   as an exemplary embodiment, more (or less) powerful systems may be made by scaling up (or down) the size of each component.

Although the principles of the present invention have been described with reference to specific embodiments, one skilled in the art will recognize that various substitutions and modifications may be made after having reviewed this disclosure.
15   The specific embodiments described above are illustrative only, and not limiting. The invention is defined by the following claims.

CLAIMS

I claim:

1. A low pollution industrial power generation system comprising:

a source of a first mixture comprising oxygen rich gas, the first mixture having less nitrogen than is present in air and more oxygen than is present in air;

a source of fuel;

a mixing unit configured to receive and mix the first mixture and the fuel to form a second mixture;

combustion chamber walls defining a combustion chamber, wherein the combustion chamber is configured to receive the second mixture; and

an igniter disposed within the combustion chamber, the igniter configured to ignite the second mixture within the combustion chamber.

2. The system of Claim 1, wherein the oxygen rich gas has an oxygen mole percentage of 50% or more.

3. The system of Claim 1, wherein the oxygen rich gas has an oxygen mole percentage of 90% or more.

4. The system of Claim 1, wherein the oxygen rich gas has an oxygen mole percentage of 99% or more.

5. The system of Claim 1, wherein the fuel includes compounds containing carbon and hydrogen, at least one of the compounds in the fuel including carbon.

6. The system of Claim 1, wherein the fuel includes natural gas.

7. The system of Claim 1, wherein the fuel includes methane.

8. The system of Claim 1 further comprising:

a source of an inert heat absorbing agent; and

a pre-mixing unit configured to receive and mix the inert heat
absorbing agent and the oxygen rich gas to provide the first mixture.

9.   The system of Claim 8, wherein the inert heat absorbing agent
includes primarily H_2O.

10.   The system of Claim 1, wherein a valve is coupled between the
combustion chamber and the mixing unit, wherein when the valve is open, the
combustion chamber is capable of receiving the second mixture from the mixing
unit.

11.   The system of Claim 1, further comprising:
        an injector configured to inject a heat absorbing agent downstream
of the combustion chamber.

12.   The system of Claim 1, further comprising:
        a temperature sensor positioned proximate an inlet of a primary
turbine stage, wherein the injection station is configured to inject the heat
absorbing agent only if a temperature at the temperature sensor is greater
than a predetermined temperature.

13.   The system of Claim 1, wherein the system is a closed loop system
and emits substantially no pollution.

14.   A method comprising:
        providing a source of a first mixture comprising oxygen rich gas,
the first mixture having less nitrogen than is present in air;
        providing a source of fuel;
        providing a mixing unit configured to receive and mix the first
mixture and the fuel to form a second mixture;
        providing combustion chamber walls defining a combustion
chamber, wherein the combustion chamber is configured to receive the
second mixture from the mixing unit; and
        providing an igniter within the combustion chamber, the igniter
configured to ignite the mixture downstream of the injector face.

15.   A method of generating industrial power comprising:

mixing a first mixture comprising oxygen rich gas with a fuel to form a second mixture, the first mixture having less nitrogen than is present in air; and

5   introducing the second mixture into a combustion chamber.

16.   The method of Claim 15 further comprising:

prior to mixing the first mixture with the fuel, mixing the oxygen rich gas with an inert heat absorbing agent to form the first mixture.

10

17.   A low pollution industrial power generation system including a gas generator, the gas generator defining a combustion chamber which is configured to generate gas generator exhaust gases, the system further comprising:

a primary turbine stage positioned downstream of the combustion

15   chamber, the primary turbine stage configured to be driven by the gas generator exhaust gases from the gas generator;

a reheater positioned downstream of the primary turbine stage, the reheater configured to receive the gas generator exhaust gases from the primary turbine stage;

20   a secondary turbine stage positioned downstream of the reheater, the secondary turbine stage configured to be driven by the gas generator exhaust gases from the reheater;

a heat exchanger positioned downstream of the secondary turbine stage, the heat exchanger configured to receive the gas generator exhaust

25   gases from the secondary turbine stage, the heat exchanger configured to transfer heat from the mainstream gases to an auxiliary fluid flow; and

an auxiliary turbine stage configured to be driven by the auxiliary fluid flow.

30   18.   The system of Claim 17, wherein the combustion chamber is configured to exhaust oxygen in the gas generator exhaust gases, the reheater further comprising a fuel inlet configured to receive fuel and configured to combine fuel with a first mixture, the first mixture comprising oxygen rich gas, the first mixture having less nitrogen than is present in air, wherein when the gas

35   generator exhaust gases have higher than an ignition temperature, spontaneous combustion occurs within the reheater.

19.   The system of Claim 17, wherein the reheater is a first reheater and the secondary turbine stage is a first secondary turbine stage, the system further comprising:

5   a second reheater positioned downstream of the first secondary turbine stage, the second reheater configured to receive and heat the gas generator exhaust gases from the first secondary turbine stage;

          a second secondary turbine stage positioned downstream of the second reheater, the second secondary turbine stage configured to receive

10   and be driven by the gas generator exhaust gases from the second reheater;

          a third reheater positioned downstream of the second secondary turbine stage, the third reheater configured to receive and heat the gas generator exhaust gases from the second secondary turbine stage; and

          a third secondary turbine stage positioned downstream of the third

15   reheater, the third secondary turbine stage configured to receive and be driven by the gas generator exhaust gases from the third reheater,

          wherein the heat exchanger is positioned downstream of the third secondary turbine stage.

20   20.   A method comprising:

          providing a combustion chamber portion configured to generate gas generator exhaust gases;

          providing a primary turbine stage positioned downstream of the combustion chamber, the primary turbine stage configured to receive and

25   be driven by the gas generator exhaust gases from the combustion chamber;

          providing a reheater positioned downstream of the primary turbine stage, the reheater configured to receive and heat the gas generator exhaust gases from the primary turbine stage;

          providing a secondary turbine stage positioned downstream of the

30   reheater, the secondary turbine stage configured to receive and be driven by the gas generator exhaust gases from the reheater;

          providing a heat exchanger positioned downstream of the secondary turbine stage, the heat exchanger configured to transfer heat from the gas generator exhaust gases from the secondary turbine stage to an auxiliary

35   fluid flow; and

providing an auxiliary turbine stage configured to receive and be driven by the auxiliary fluid flow.

21.   An industrial power generation method comprising:

5   combusting gases in a combustion chamber to form gas generator exhaust gases;

expanding the gas generator exhaust gases from the combustion chamber through a primary turbine stage to generate a first amount of power;

10   reheating the gas generator exhaust gases from the primary turbine stage;

expanding the gas generator exhaust gases from the reheater through a secondary turbine stage to generate a second amount of power;

transferring heat from the gas generator exhaust gases from the

15   secondary turbine stage to an auxiliary flow; and

expanding the auxiliary flow in an auxiliary turbine stage to generate a third amount of power.

22.   The industrial power generation method of Claim 21, wherein

20   combusting gases comprises burning gases in a combustion chamber to form the gas generator exhaust gases including oxygen, the method further comprising:
        adding fuel to the reheater.

23.   An industrial gas generator comprising:

25   a source of heat absorbing agent in a liquid phase; and

a combustion chamber wall defining a combustion chamber, wherein the combustion chamber walls define a plurality of channels, the plurality of channels connecting the source to the combustion chamber, wherein the source is configured to inject the heat absorbing agent through

30   the plurality of channels into the combustion chamber, wherein the heat absorbing agent is configured to receive heat from the combustion chamber through the combustion chamber walls as the heat absorbing agent passes through the plurality of channels such that the heat absorbing agent evaporates before injection into the combustion chamber.
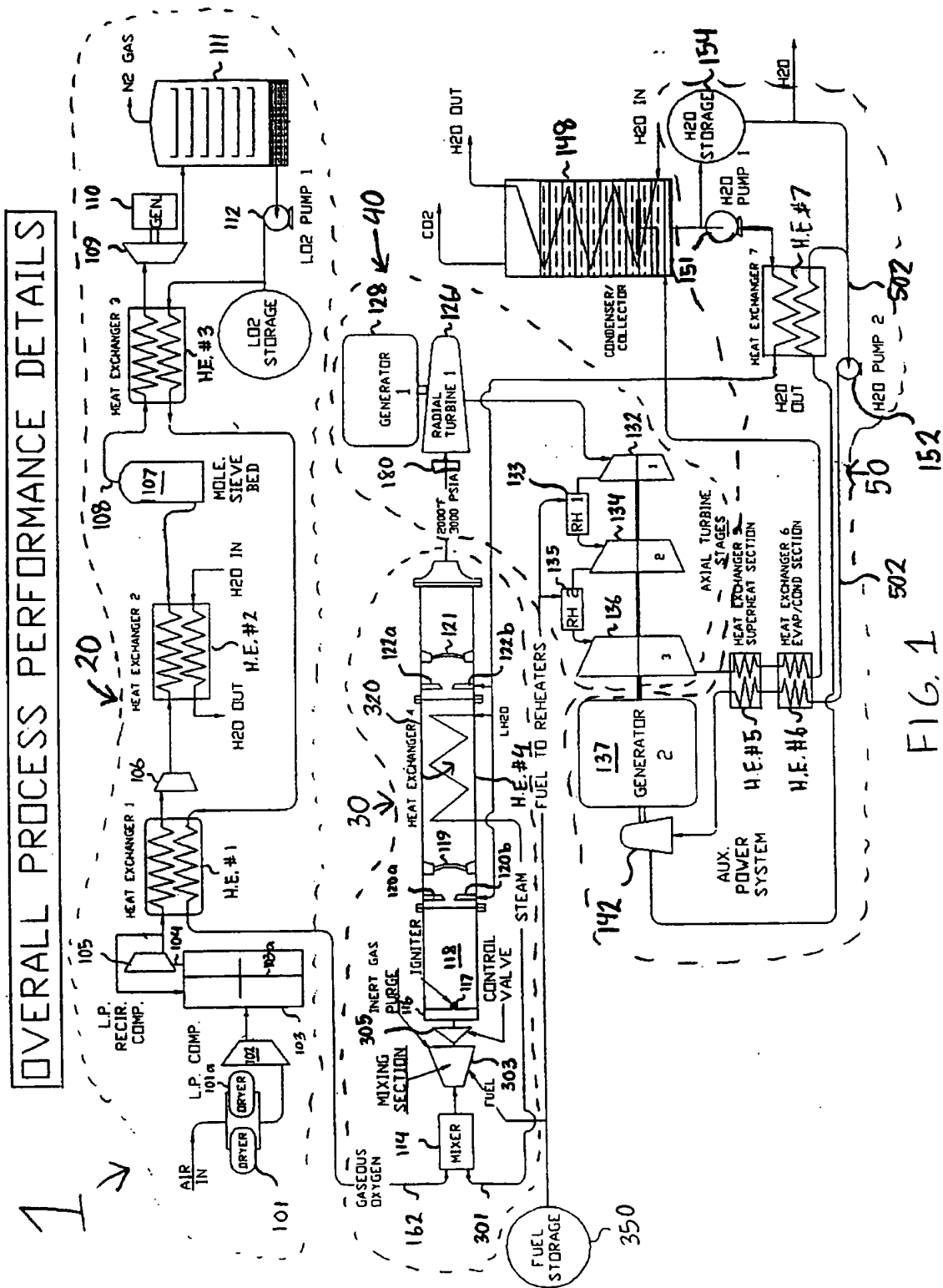
35

24.   The generator of Claim 23, wherein the heat absorbing agent evaporates as the heat absorbing agent passes through the plurality of channels thereby cooling the combustion chamber wall.

5   25.   The generator of Claim 23, wherein the combustion chamber walls comprise a plurality of stacked discs having channels formed therein.

26.   An industrial gas generation method comprising:
           providing a source of heat absorbing agent in a liquid phase; and
10   providing a combustion chamber wall defining a combustion chamber, wherein the combustion chamber walls define a plurality of channels, the plurality of channels connecting the source to the combustion chamber, wherein the source is configured to inject the heat absorbing agent through the plurality of channels, wherein the heat absorbing agent is
15   configured to receive heat from the combustion chamber through the combustion chamber wall as the heat absorbing agent passes through the plurality of channels.

27.   An industrial gas generation method comprising:
20   injecting a heat absorbing agent in a liquid phase through a plurality of channels defined in a combustion chamber wall and into a combustion chamber, wherein the heat absorbing agent changes from a liquid phase to a gaseous phase as the heat absorbing agent passes through the plurality of channels.

25

OVERALL PROCESS PERFORMANCE DETAILS

FIG. 1

OXYGEN PRODUCTION SYSTEM

FILTER DRIER

101

CONT. MEMB. COLUMN

102

L.P. COMP.

105 103a 103v 103iii

103i 103ii

103 103b IN₂

L.P. REC. COMP 104

H.E. #1

106

H.P. COMP.

H2O OUT H2O IN

H.E. #2

107

MOLECULAR SIEVE BED

108

20

HI.PRES. GASEOUS OXYGEN 3.4#/SEC.

H.E. #3

113

LOX PUMP

EXP. TURB. 112

109

GEN.

110

N2 OUTLET

148

DISTIL. TOWER

FIG. 2

FIGURE 3 * GAS GENERATOR

FIG.3

PREMIXING SECTION   COMBUSTION CHAMBER   FINAL PREPARATION

FIGURE 4 * MAIN POWER SYSTEM

GENERATOR 1 — 128

RADIAL TURBINE 1 — 126

10

EXHAUST FROM GAS GENERATOR — 124

40

FUEL TO REHEATERS

RH 1 — 131

RH 2 — 133

RH 3 — 135

AXIAL TURBINE STAGES

1 — 132

2 — 134

3 — 136

TO AUX. POWER EXCHANGERS & GAS RECOVERY SYSTEM

137

FUEL STORAGE

GENERATOR 2

FIG. 4

FIGURE 5 * AUXILIARY POWER SYSTEM

~50

TURBINE EXHAUST FROM
MAIN POWER SYSTEM

RADIAL
TURBINE 2

GENERATOR
2

~137

502

1200°F
1000 PSIA

142

230°F
10 psia

502

H.E.#5
HEAT EXCHANGER 5
SUPERHEAT SECTION

H.E.#6
HEAT EXCHANGER 6
EVAP/COND SECTION

502

RECYCLED
TO GAS
GENERATOR

TO GAS
RECOVERY SYSTEM

H.E. #7
HEAT EXCHANGER 7

152

H2O PUMP 2

502

H2O STORAGE ~154

H2O

13

151
H2O
PUMP 1

502

MAKE-UP H2O

502

FIG. 5

6/8

610

6B

620

FIG. 6A

610

624

620

622

622

FIG. 6B

Mainstream gas out

131

600

603

602

601

604

fuel in

Mainstream gas in

FIG. 7

FIG. 8A

FIG. 8B

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   F02C3/22   F02C3/30   F01K21/04   F02C3/34

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6   F02C   F01K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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| X | Further documents are listed in the continuation of box C. | | X | Patent family members are listed in annex. |

* Special categories of cited documents :

"A" document defining the general state of the art which is not
    considered to be of particular relevance
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    other means
"P" document published prior to the international filing date but
    later than the priority date claimed

"T" later document published after the international filing date
    or priority date and not in conflict with the application but
    cited to understand the principle or theory underlying the
    invention
"X" document of particular relevance; the claimed invention
    cannot be considered novel or cannot be considered to
    involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention
    cannot be considered to involve an inventive step when the
    document is combined with one or more other such docu-
    ments, such combination being obvious to a person skilled
    in the art.
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
9 February 1999	17/02/1999

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INTERNATIONAL SEARCH REPORT

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